CONTROL OF VORTEX BREAKDOWN OF FLOW OVER A DELTA WING

By

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DEPARTMENT OF AEROSPACE ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY, KANPUR

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A *Thesis* Submitted
in Partial Fulfillment of the Requirements
for the Degree of
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by

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CERTIFICATE

It is certified that the work contained in this thesis entitled "*Control of vortex breakdown of flow over a delta wing*" , by *Nandan Kumar Sinha*, has been carried out under my supervision and that this work has not been submitted elsewhere for any degree

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Dedicated to

my loving parents

ABSTRACT

In the present investigation, the vortical flow over delta wings has been studied and an attempt has been made to control the vortex breakdown using suction of the vortex core through a probe at the trailing edge All the experiments have been carried out in the low speed, low turbulence wind tunnel over a 70 degree sweep delta wing Smoke flow visualisation with Laser light sheet as an illuminating medium and pressure measurements using seven-hole pressure probe in the vortical flow field has been done Both qualitative and quantitative analysis has been done for the flow in the vortex

It was seen that suction of the vortex core is quite successful in controlling the vortex breakdown Flow visualisation gives all the detail of the flow in the vortical structure and complete vortex breakdown phenomena has been observed successfully Flow visualisation has also confirmed the effectiveness of the control method using suction Pressure measurements has given a quantitative picture of the flow and vortical structure is quite visible from the contour plots

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NOMENCLATURE

ε	average roughness
D	diameter of the pipe
L	distance between the pressure taps
ρ	density of air
μ	viscosity of air
Δp	pressure difference at the pressure taps
f	friction factor
V_{av}	average velocity in the pipe
Q	mass flow rate
A	area of cross section of pipe
Re	Reynolds number
Re_D	Reynolds number of the flow in the pipe based on pipe diameter
S	half span of the wing

INTRODUCTION

Modern fighter aircraft are required to operate in a flight regime that requires the maximum maneuverability and controllability possible to be effective in the combat arena Requirements for high maneuverability necessarily dictate that aircraft must fly at high angles of attack The required aerodynamic performance of such an aircraft configuration is achieved by using slender, highly swept, low aspect ratio wings Delta wing is the configuration which fulfils these requirements and is commonly used for the purpose The dominant feature of the delta wing is characterized by the vortical flows over the leeward surface of the wing

At moderate and high angles of attack, the flow separates from the sharp leading edge of slender wings These flow separation usually take the form of two free shear layers joined to the leading-edges of the wing and rolling up to form spiral shaped primary vortices above the upper surface of the wing as shown in fig [1a]

The vortices over the wing induce additional velocities on the upper surface of the wing, thus creating a suction side which is shown in fig [1b] by pressure minima beneath the vortex axes Accordingly, an additional lift force occurs which depends non-linearly on the angle of incidence(fig [1c])

Due to the leading-edge vortices the flow at the wing surface is directed outwards The steep pressure gradient between the minima of pressure and the leading edge causes flow separation which usually takes the form of a small secondary vortex, the sense of rotation of which is opposite to that of the primary vortices The primary vortex, is fed by the vorticity from the boundary layer along the leading edge of the wing The secondary vortex immediately adjacent to it, however, is fed by vorticity from the boundary layer on the surface of the wing On the other hand, the secondary vortex immediately next to the edge of the wing is fed by that portion of the vorticity from the edge of the wing that is peeled off from the separating shear layer feeding the primary vortex All of these vortices are non-axisymmetric

One of the most interesting phenomena associated with leading-edge vortices is their breakdown The breakdown or bursting, as it is commonly called, refers to a sudden and dramatic structural change that usually results in the turbulent dissipation of the vortex Vortex bursting is characterized by (a) a sudden deceleration of the axial flow in the vortex core, (b) the formation of small recirculatory region, (c) a decrease in the circumferential velocity and (d) an increase in the size of the vortex As observed experimentally using flow visualization techniques, vortex bursting is characterized by abrupt transition from a jet-like to a wave like core of the vortex, accompanied by a substantial increase in turbulent activity There is a sudden expansion of the vortex about a rapidly decelerating core, with subsequent vortex disintegration and loss of orderly vortical flow The schematic representation of complete vortex breakdown phenomena is shown in fig [2]

Several distinct types of vortex breakdown have been identified, however the most common form of breakdown on delta wings are the bubble and spiral types The bubble and spiral modes of vortex breakdown are illustrated in fig [3] The bubble or "axisymmetric" mode of vortex breakdown is characterized by a stagnation point on the swirl axis, followed by an oval shaped recirculation bubble The bubble is nearly symmetric over most of its length, but the rear is open and asymmetric

The spiral mode of breakdown is characterized by a rapid deceleration of the core flow followed by an abrupt kink, at which point the core flow takes the form of a spiral that persists for one or two turns before breaking down into large scale turbulence

When vortex breakdown occurs, the aerodynamic stability and control characteristics of the wing change dramatically Once the angle of attack is large enough for the vortex breakdown to have crossed the trailing edge and moving upstream, the wing experiences a substantial change in the local pressure field, producing a decrease in the lift curve slope and an increase in the pitching-up moment At sufficiently high angles of attack, the entire vortex flowfield has undergone breakdown so that a gross separation without concentrated vortex features exists over the wing and all the

advantages of using this wing is gone That is where the need for controlling these vortex flows on the aircraft arises

Both active and passive control techniques have been tried for many years for controlling this vortex breakdown Some of the most promising methods for forebody vortex control over fighter aircraft are movable forebody strakes, rotatable nosetip devices, blowing/suction on the forebody surface and different forms of small perturbations

Most of the research efforts to date on vortex control techniques have been focused on generic or specific fighter aircraft configuration representing present day aircraft Future aircraft configurations, however, are tending towards shapes and concepts that are beyond the present aerodynamic database

LITERATURE SURVEY

The delta wing, due to its special features, has always been an interesting research topic in the history of aeronautics The vortical flows over the delta wing has been discussed from time to time and a constant approach for understanding the phenomena of leading-edge vortices and their breakdown over the wing has been followed for as many as 50 years The British-French "CONCORDE" project in 1950's, the similar Russian "TU-144" design, and the interest in slender hypersonic vehicles have added impetus to the study of leading-edge vortex flows The control of these leading-edge vortices has always been the centre of attraction for improving the advantages derived from using the slender-type delta wing and from the point of view of stability

Throughout these years, many experimental investigations with different set-up and parameters have been carried out With different delta wing configurations like varying aspect-ratios, sweep-angles, leading-edge curvature and at different experimental conditions like different Reynolds numbers at different angles of attack, using different types of visualisation techniques people have tried to understand the physics of the flow and the theory behind the vortex breakdown Over the years, different types of control techniques both passive and active have been tried and recommended to control the vortical flows

The leading-edge vortices over delta wing, according to Polhamus[9], produce large suction on the wing surface and account for the additional lift which can be upto 30% of the total lift generated by delta wing aircraft at moderate angles of attack However, beyond a critical angle of attack, a phenomena called vortex breakdown occurs, which completely destroys the advantages gained in terms of lift Therefore, vortex bursting is an important limiting factor on aircraft performance and hence is a subject of study It has been studied both experimentally[1-5] and theoretically[6-7], for more than two decades

Using 5-hole pressure probe, Dietrich[1] has done pressure measurements in the vortical flow field at four planes perpendicular to the free stream direction to give the magnitude and direction of the velocity vector Flow field was found to be non-conical and the presence of secondary vortices was found The secondary vortices has mainly

two effects on the flow field, (a) there is a displacement effect by which the centre of the leading-edge vortex is shifted inwards and upwards, corresponding to an inward movement and (b) a reduction in the suction peak of the pressure distribution Secondly, there is a vorticity effect, which increases suction in the region of the secondary vortex The effects are small for turbulent boundary layer and larger for laminar boundary layer The secondary vortex decays downstream of the wing trailing-edge Atta & Rockwell [8] in their study about the secondary vortex found that the secondary vortex adjacent to the leading-edge is fed by vorticity shed from the edge, while its inboard neighbour is fed by vorticity from the wall boundary layer The secondary vortex close to leading-edge has the similar behaviour as the primary vortex In the experimental work [1-4] the vortex breakdown phenomenon has been discussed and it has been related to the pressure field Vortex bursting is characterized by loss of static pressure

Greenwell & Wood [7] gave a simple potential flow model using a shape parameter and showed that the model was compatible with the results from flow visualisation techniques and different surface pressure measurements in the vortex bursting region Payne et al [6] has provided a complete structure of the vortical flow before and after vortex breakdown using smoke flow visualisation with laser light sheet technique on different types of wing At low Re, at a given angle of attack, increasing sweep angle moves the vortex breakdown(VBD) location aft on the wing, VBD location oscillates at a given set of conditions VBD are of two types spiral and bubble Using Laser Doppler Anemometry(LDA) he showed that there is a development of jet-like core flow in which velocity reaches three times the freestream velocity before breakdown, after the VBD the velocity profiles become wave-like in nature

A detailed study of experimental investigations of vortex breakdown has been given by Leibovich[10] Under different experimental investigations LeMay et al [11] observed that oscillatory dynamic pitching of a delta wing in a sinusoidal fashion, developed a hysterisis in the chordwise location of vortex breakdown Hebbar & Leedy[12] in their water tunnel investigations over fighter model showed that below 45 degrees the flow characteristics are governed by vortex interaction along the upper surface of the fuselage and wings coupled with nose generated vortices Stahl et al

[13] observed setting the wing in the wind tunnel at a distinct yaw angle, at high incidence, brought on only slight vortex flow asymmetry Apex influences the occurrence of vortex flow asymmetry Miau et. al [14] on a 50-degree sweep delta wing carried out flow visualisation and velocity measurements with different leading edge profiles and showed that the bevelled leeward surface produces weak vortices, however, bevelled windward surface produces stronger vortical flows over the upper surface of the delta wing

As mentioned earlier, the vortex breakdown has always been a limiting factor in the sense that it demeans or destroys all the advantages derived from using this type of wings Then, many control techniques, both active and passive, have been tried in the past to control the vortical flows Lowson[15], in detail, has examined the reason for the variation in the vortex breakdown location in results from various investigators He found that support interference, tunnel effects and Reynolds number has very little effect The detail geometry of the wing particularly the apex is found to be the most important factor in determining the position of vortex breakdown A small apex flap on the leading edge could be used to control the vortex breakdown location on a delta wing Gangulee[16] using a flow deflector on the leeward side has shown that at low speed, it is effective but at high speeds the deflector promotes vortex bursting By changing the geometry of the deflector vortex behaviours could be changed which in turn changes the forces and moments Hebbar et al [17] working on a double delta wing, which is the actual configuration of a fighter aircraft confirmed that diamond fillets at the strake/wing junction implied lift augmentation during side-slip motion

In his numerical investigations Kern[18] has tried various fillets shapes at the junction of the double delta wing He found fillets are effective for controlling roll The vortex-vortex interaction can be controlled using fillets resulting in enhanced lift and longitudinal control Through asymmetric deployment of the fillets, additional directional control may be achieved This is supported by Hebbar et al [17] Klute et al [3] tested an apex flap for fixed and maneuvering delta wings They found that the drooping apex flap can delay vortex breakdown by an angle of 8 degrees beyond the steady flow breakdown angle of attack

Under active control techniques, Helin & Watry[19] using trailing edge jets found that at moderate angles of attack it is possible to delay the bursting location upto 18% of the chord by increasing the flow velocity from the exhaust ports In addition, at higher angles of attack, the trailing-edge jets stabilized the asymmetric separated vortices by reattaching the flow and moving the burst location aft on the wing Entrainment from jets or engines at the trailing-edge of the wing can be used to control the leading-edge vortices Seginer & Salomon[20] showed that spanwise blowing achieve the same lift augmentation produced by a canard, without drag penalty Paramenter & Rockwell[21] in their water tunnel dye flow visualisation study observed from fig [4] that suction through a probe at the core is very effective in stabilising the core

OBJECTIVE OF THE PRESENT STUDY

From the literature survey it is found that still not many vortex breakdown control techniques, both active and passive, have been tried and the vortex breakdown phenomena has not been understood completely

In the present work,

(a) An active control technique, using suction of the vortex core through a probe attached to a suction device and kept at the trailing edge of the wing has been tried to control the vortex breakdown A quantitative approach has been taken to understand the effect of various parameters on the control method applied

(b) The full vortical structure has been studied using Smoke Flow Visualisation Technique with Laser Light Sheet as an illuminating medium A detail study of the vortex core has been done to understand the vortex breakdown phenomenon With suction, flow visualisation has been done to show the effectiveness of the method

(c) Finally, pressure measurements using seven-hole probe have been done in the vortical flow field to understand the vortical structure quantitatively

EXPERIMENTAL SET UP

Facility

The experiment was conducted in the low speed low turbulence wind tunnel in the department of Aerospace Engineering at IIT, Kanpur This is an open circuit continuous flow wind tunnel with a test section of 0 6m×0 6m×3m, a maximum wind speed of 40m/sec and a contraction ratio of 16 The diffuser half angle is about 5 degrees The turbulence level is less than 0 2% A 25hp DC motor drives a blade propeller fan of 1 5m diameter A sketch of the facility is shown in fig [5]

Model Geometry and Mounting System

The experimental model made of plexiglass is a delta wing with a sweep angle of 70 degrees, a root chord of 34 8cm and the thickness of the model is 5mm A sketch of the model is shown in fig [6] A scale has been attached to the mounting system to the angle of attack of the delta wing The model mounting system is a mild steel block supported on a aluminium cylindrical rod which is tightened from below The block is supported on bearings mounted on the cylindrical rod to provide the model yaw angle adjustment The block holds the model at any angle of attack

Instrumentation

Suction device

For controlling the vortex breakdown suction was applied at the trailing-edge through a probe at the vortex core which was connected to a suction device A sketch of the experimental set-up with suction device is shown in fig [6] A Variac was used to control the suction A manometer was attached to the pressure taps which were connected at 80 pipe diameter in the fully developed flow region on the side of the connecting pipe to give the pressure difference at different flow rates Mass flow rates were calculated from the suction pressure

Pressure measurements

The pressure measurement was done in the one half plane of the delta wing to get a quantitative picture of the vortical flow The pressure measurement set-up using seven hole probe has been shown in he figure[7] All the pressure ports of the seven-hole probe are connected to multiplexer unit in the order shown in the figure[7] and the static tube from pitot-static tube is connected to the static of the multiplexer unit which is the reference for all the pressures The total pressure tube from the pitot-static tube is connected to the first channel of the multiplexer unit An electronic manometer of rating 199 99mm H_2O at 100% is connected to the multiplexer unit to read the pressure signal at a selected port, which is selected by the multiplexer unit The port selection in the multiplexer unit is done by sending 8 digital inputs from the computer through a high speed A/D board Pressure signal from the micro-manometer is also collected by using this A/D board and LabVIEW based data acquisition program

Flow Visualisation Technique

To study the vortical structure and the vortex breakdown phenomena with and without suction Smoke Flow Visualisation Technique was used Smoke of vaporised kerosene oil was introduced upstream of the model and the flow field over the delta wing was illuminated using Laser Light Sheet The light generating system was mounted on a system which gave it a freedom to rotate the sheet in a plane The vortical patterns over the delta wing were photographed using three CCD cameras which was connected to TV monitor and VCR to record the motion picture of the flow field A detail of the laser light sheet generating system and the complete visualisation arrangement has been provided in the fig [8] The Laser beam coming out from the Laser Unit is modulated and then sent through a fibre optic cable to the Oscillating Mirror System The Laser beam falls on the mirror and the reflected beam is made to fall on the Cylindrical lens from where the output is a Laser sheet

The Laser light sheet technique is especially suitable for visualisation of local flow fields It provides significant insight and better understanding of the complex flow

structures Laser light sheet is generally used for light sheet generation, because a monochromatic light suffers no dispersion while passing through optical elements and it has low divergence, therefore, it has sufficiently high intensity in the flow visualisation direction, and a Laser beam is easy to handle In this case while developing new body shape and performing dynamic optimisation, it can be quickly detected how changes to object geometry affect the flow field The Argon-ion laser is preferred in its TEM00 mode to get a smooth and guassian light distribution in the plane For 60cm×60cm cross-section, 6 watts of laser power is sufficient By means of video film recording unsteady and spatial structure of the flow can be analysed effectively

Results And Discussion

The vortex breakdown location was noted down with and without suction using smoke flow visualisation technique The light sheet was passed through the vortex diametrically in the core so that the vortex bursting location was visible As the point, where the bursting occurs, starts moving downstream when the suction is applied the shift in that point's location was noted down This was done for two different angles of attack and three different Reynolds numbers Suction was applied with different volume flow rates by changing the Variac settings which controlled the voltage applied to the blower and hence the rpm All the details of volume flow rate calculation has been given in appendix

The flow visualisation using Laser light sheet technique was done to observe the details of the flow in the vortex with and without suction at a fixed Reynolds number and fixed angle of attack 30 degrees The flow pictures were taken using three CCD cameras and video recording through colour TV monitor This was done with light sheet travelling all over the wing section-wise The suction was applied through a 5mm diameter probe adjusted to be at the core height of the vortex and kept at the trailing edge of the delta wing Flow pictures were recorded to see the effect of suction on the vortex breakdown

Finally, Pressure measurements was done using seven-hole probe in the half plane of the delta wing at 73% of root chord location The probe was traversed to cover one full vortex This was done at 20deg angle of attack and $Re = 9\ 75 \times 10^4$ Data was taken at 450 points covering the one full vortical structure Data was plotted to give the static pressure and dynamic pressure contour plots in the complete half plane

Control With Suction

In order to control the vortex breakdown location suction was applied at various volume flow rates at two different angles of attack and three different Reynolds numbers The volume flow rates as suction pressure is increased, is provided in

Table[1] For different conditions shift in vortex breakdown location was noted down The experimental data obtained are plotted in figs [9-11] All the figures are for non-dimensionalized flow rates vs vortex breakdown location(VBD) at different experimental conditions The volume flow rate of the flow being sucked has been non-dimensionalized with reference to the volume flow rate through a section having the same area as that of the planform of the wing From the figs [9-11], for different angles of attack and Re it is observed that the suction of the vortex core through a probe kept at the trailing edge is quite successful in controlling the vortex breakdown location From fig [9] it is observed that at 31deg angle of attack there is a regular pattern of shift in VBD location with different Reynolds numbers and volume flow rates Shift in VBD location is less as the volume flow rate is increased with the increase in Reynolds number

From figs [10-11] it is observed that as Reynolds number increases, there is a shift in the VBD location downstream, which is because the flow has more energy and it is able to sustain further downstream As the suction is applied the flow with low Re gets sucked fast, but, as the Re increases it takes high suction pressure to be applied to VBD location to finally shift to the TE This is observed at both the angles of attack

At 34 deg angle of attack(fig [9]), we observe that VBD location shifts downstream as the volume flow rate is increased which is similar to the observation at 31deg angle of attack(fig [9]) But, at this angle of attack, VBD occurs early on the wing As the Re increases, we see that the regular pattern of the flow is disturbed and there is no regularity observed in the shift in VBD location as the Reynolds number increases and the volume flow rate is increased The could be because the VBD location is not stable over the wing This happens at high $Re = 13\,0\times10^4$ As is quite clear from the figs [10-11], at low $Re1 = 525\times10^4$ and $Re2 = 9\,0\times10^4$ (fig [10]) we have a regular pattern for both the angles of attack but at high Re i e $Re3 = 13\,0\times10^4$ (fig [11]), the pattern is disturbed and as the volume flow rate is increased, there is more shift in the VBD location at 34deg angle of attack than at 31deg angle of attack This could be because of the unsteadiness in the flow

From fig [10] it can also be observed that the minimum volume flow rate required for the vortex breakdown not to occur over the wing increases as Reynolds number increases from Re1 to Re2 but for Re3(fig [11]) the minimum volume flow rate is found to be less at both the angles of attack as compared to the flow at low Reynolds number

Flow Visualisation

Motion picture of the vortical structure was recorded using Smoke Flow Visualisation with Laser Light sheet as illuminating medium and pictures were taken to get the complete detail of the flow inside the vortex with and without suction All the pictures have been shown in figs [12-15] Flow visualisation confirms the success of the method applied to control the VBD In fig [12] we see the vortices on both the leading edges of the delta wing They are symmetric and having a core At the mid chord of the wing we see outside flow being sucked in This is because the vortices are low pressure field which tend to suck the flow from outside From pictures in figs [13(a g)] we observe how the breakdown takes place This is a complete phenomena of bursting cycle and related unsteadiness of the flow The core diameter grows and core starts expanding and finally it bursts like bubble Increase in core diameter indicates that the VBD location is moving upstream and the decrease in the core diameter is because the VBD location has moved downstream and the bursting is delayed This is because of the unstable nature of the vortex as it bursts All the pictures in figs [13(a-g)] have been taken at the same chordwise location to give a complete detail of the flow as the vortex bursts

As the suction is applied at the core, we see from pictures in figs [14(a),14(b),15(b)] that core diameter reduces to its unburst size, this is because, as mentioned earlier, the vortex breakdown location has moved downstream and the bursting has been delayed When the suction is applied it sucks the core and consequently the VBD location downstream and the bursting gets delayed As can be observed from the further downstream pictures in figs [14(a) 14(b)] the core diameter is the same as one at the upstream location and the core is intact it is because the vortex bursting has been delayed Figs [15(a) 15(b)] shows the structure of the flow at the trailing edge of the

wing where the probe has been kept for the suction From fig [15(a)] which is without suction it is observed that the flow has completely bursted and the core is no more visible this is because of the introduction of the probe tip in the vortex core When the suction is applied the core becomes visible and stable at the probe tip as is observed from fig [15(b)]

The flow visualisation study confirms the success of applying control with suction at the core of the vortex

Flowfield Pressure Measurements

Pressure measurements was carried out using seven-hole pressure probe in the one half plane of the delta wing covering one full vortex An analysis was done with the calibration constants for seven-hole probe obtained by Abhishek[22] to get the static and dynamic pressure contour plots The results obtained are shown in fig [16] The location (-0 00 0 00) in the fig [16] is the root chord and (-1 00, 0 00) is the leading-edge of the wing Z/S is the non-dimensional vertical location over the wing and X/S is the non-dimensional spanwise location of the seven-hole pressure probe In The fig [16] all the pressures are in mm of H_2O From fig [16], it can be observed that the maximum dynamic pressure 3 4 mm H_2O and the minimum static pressure -2 8 mm H_2O is occurring in the region Z/S(0 15- 0 29) and X/S(-0 54 - -0 8) We can conclude from this that there is a vortex core lying in this region As we move away from this region the dynamic pressure decreases and the static pressure increases The static pressure increases to -0 4 mm H_2O and dynamic pressure decreases to 1 4 mm H_2O at X/S(-0 45) As the probe is traversed towards the root chord there is not much variation seen in the pressure field, where the flow is away from the vortical region The vortical structure lies between 42% and 92% of the half span The core seems to be lying around 60% of the half span from the root chord, which is quite agreeable with the previous works on the delta wing vortices

CONCLUSIONS

The results shows that the controlling of vortex breakdown with suction of the core through a probe kept at the trailing edge is quite successful As the suction pressure and therefore the mass flow rate is increased the probe at the trailing edge of the delta wing is able to suck the VBD location of the flow at all Reynolds numbers and angles of attack The flow visualisation results have been in conformity with the quantitative conclusions The laser light sheet technique used for flow visualisation is very much successful in giving the details of the flow inside the vortex and the complete bursting cycle has been observed clearly The control of the vortex when the suction is applied is clearly noticeable in the pictures The pressure measurements using seven-hole probe hasn't given the expected contours but from the contour plots the location of the vortex and the vortex core has been found successfully

APPENDIX

The formulae used for Volume Flow Rate calculation is given below in equations(1-7)

Where

$$\varepsilon = 0\ 00015mm \quad \text{(for drawn tubing)}$$

$$D = 15mm \quad \text{(pipe diameter)}$$

$$\frac{\varepsilon}{D} = 0\ 0001$$

$$\rho = 1\ 22Kg/m^3$$

$$\mu = 1\ 8 \times 10^{-5} Ns/m^2$$

$$L = 275mm \quad \text{(spacing between the pressure taps)}$$

Δp was taken from manometer reading and from eqn(6) f was calculated and finally the volume flow rate Q was calculated from eqn(7)

$$\Delta p = f\ \frac{1}{2} \rho V_{av}^{\ 2} \text{ ---(1)}$$

$$V_{av} = \frac{Q}{A} = \left(\frac{4}{\pi}\right)\left(\frac{Q}{D^2}\right) \text{---(2)}$$

from eqn(1) and eqn(2) we get an expression for Δp as

$$\Delta p = f\ \left(\frac{8}{\pi^2}\right)\left(\frac{\rho L}{D^5}\right) Q^2 \text{---(3)}$$

$$\frac{1}{\sqrt{f}} = -2\ 0 \log_{10}\left[\frac{\varepsilon/D}{3\ 7} + \frac{2\ 51}{(\mathrm{Re}_D\sqrt{f})}\right] \text{(Colebrook Formula)-----------(4)}$$

$$\mathrm{Re}_D = \left(\frac{4}{\pi}\right)\left(\frac{\rho}{\mu D}\right) Q \text{ -------------------------------------(5)}$$

Substituting eqn(5) in eqn(4) gives the simplified Colebrook formula related to pressure difference Δp as,

$$\frac{1}{\sqrt{f}} = -2.0\log_{10}\left[\frac{\varepsilon / D}{3.7} + \frac{2.51\sqrt{k_1}}{k_2\sqrt{\Delta p}}\right] \text{--------------------------------} (6)$$

Where

$$k_1 = \left(\frac{8}{\pi^2}\right)\left(\frac{\rho L}{D^5}\right) = \frac{\Delta p}{f Q^2} = 3.58 \times 10^5 \quad \text{from eqn(3)} \text{ ----------------} (7)$$

and

$$k_2 = \left(\frac{4}{\pi}\right)\left(\frac{\rho}{\mu D}\right) = \frac{Re_D}{Q} = 5.75 \times 10^6 \quad \text{from eqn(5)}$$

The volume flow rates thus obtained for various suction pressure are given in Table[1]

FURTURE SCOPE OF THE WORK

As we have already seen that the suction is quite successful in controlling the vortex This is one type of active control, various active and passive control methods could be tried to get more efficient methods One could make measurements in the flow with and without suction and compare the two results to get a comparative picture Here in this work flow visualisation has been done with the light sheet travelling only vertically all over the wing, a better view of vortex bursting and unsteadiness in the vortical flow and the control of the vortex breakdown can be obtained by passing the light sheet parallel to the core trajectory Finally for the pressure measurements one can take it at different chordwise locations and relate the flow fields as it moves downstream In addition forces and moments are needed to be measured to see the effectiveness of the method used

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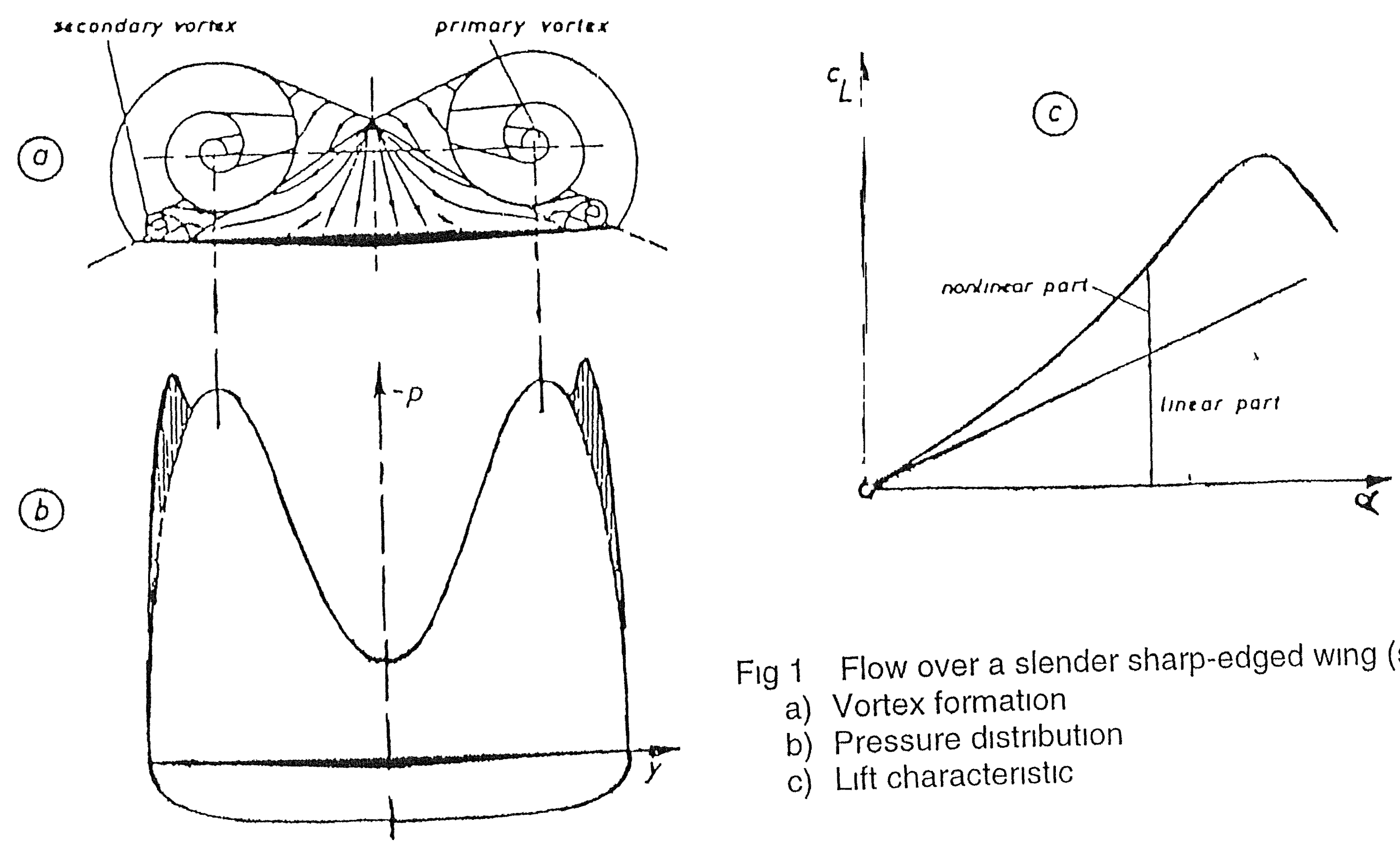


Fig 1 Flow over a slender sharp-edged wing (schematic) [Ref 1]
a) Vortex formation
b) Pressure distribution
c) Lift characteristic

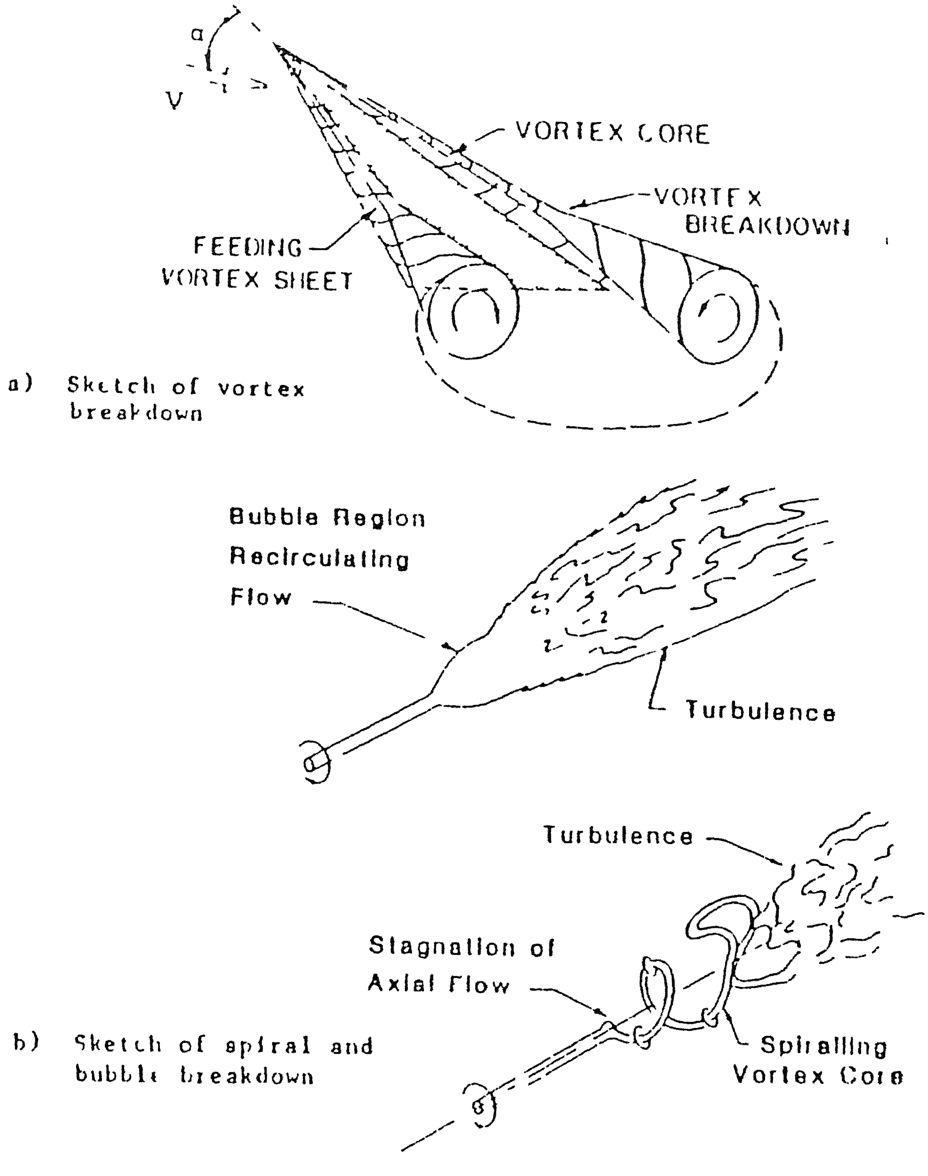


Fig 2 Leading edge vortex breakdown on a delta wing

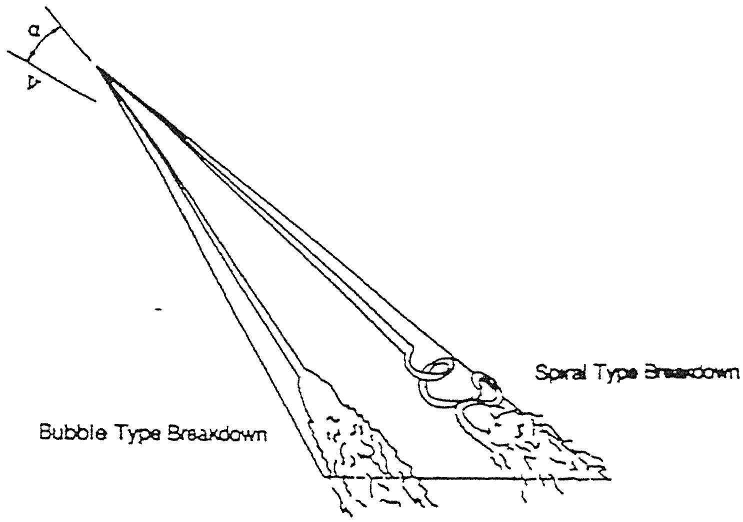


Fig 3 Flow over a delta wing bubble and spiral types of vortex breakdown [Ref 6]

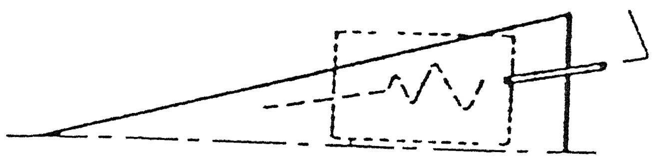


Fig 4 Schematic representation of vortex control through a probe [Ref 21]

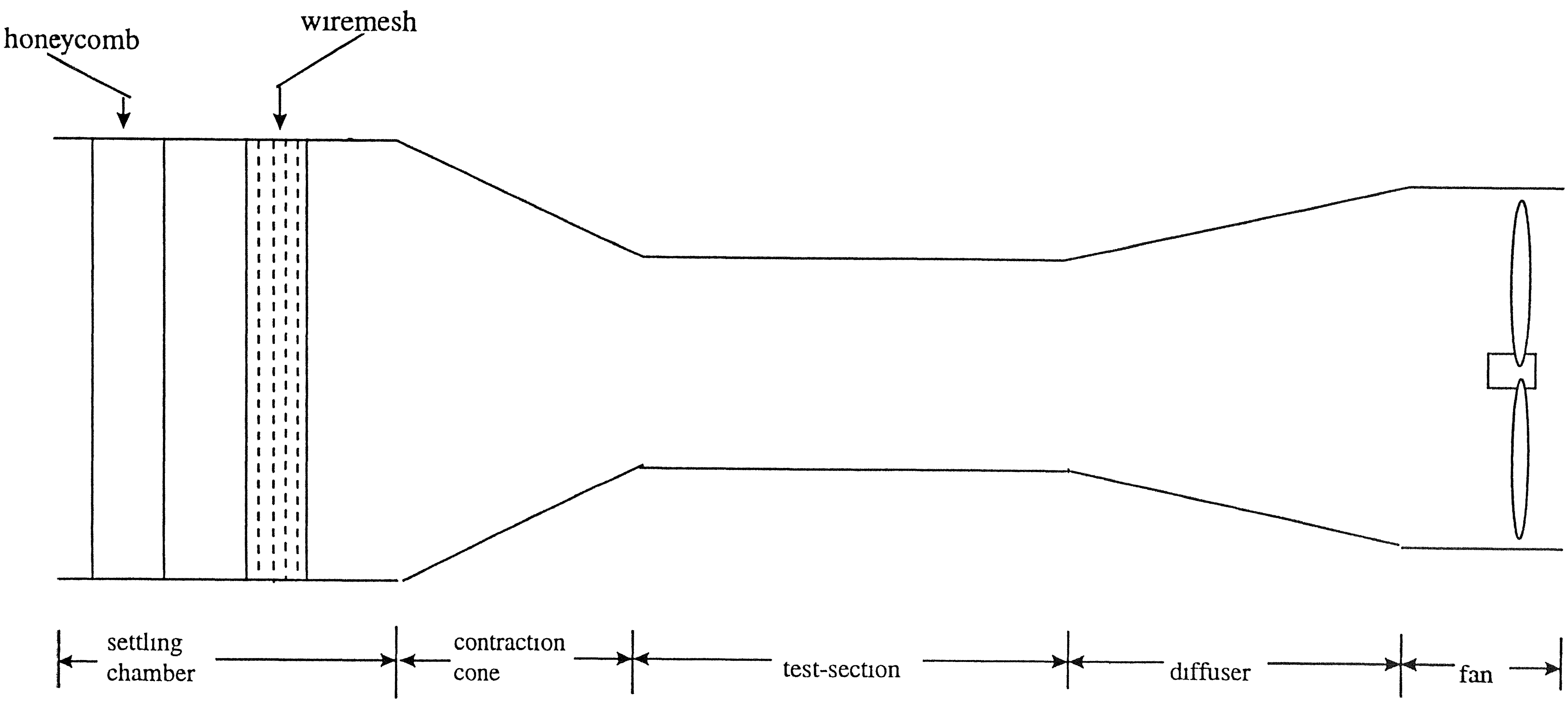


Fig 5 A Sketch of the Wind-Tunnel

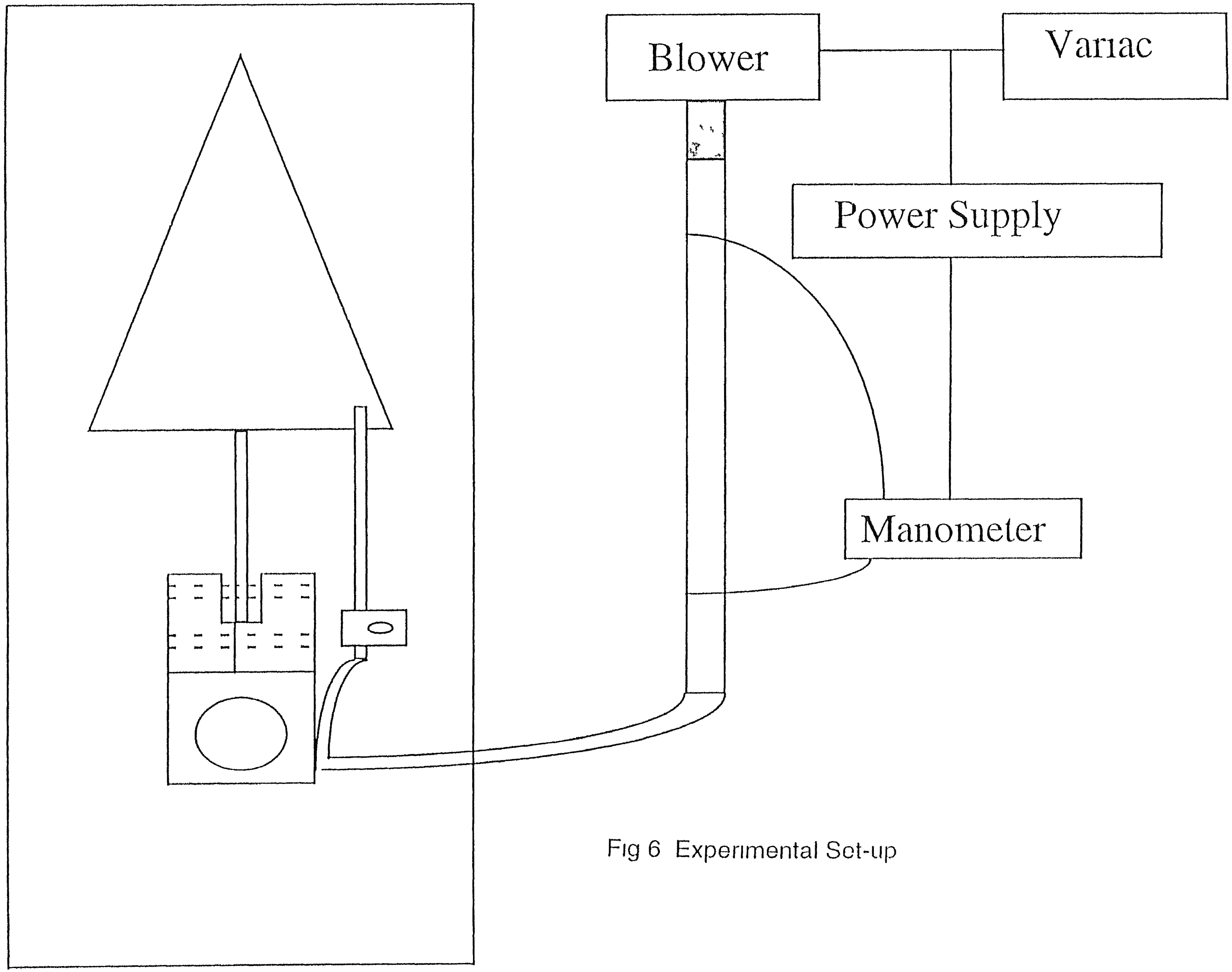


Fig 6 Experimental Set-up

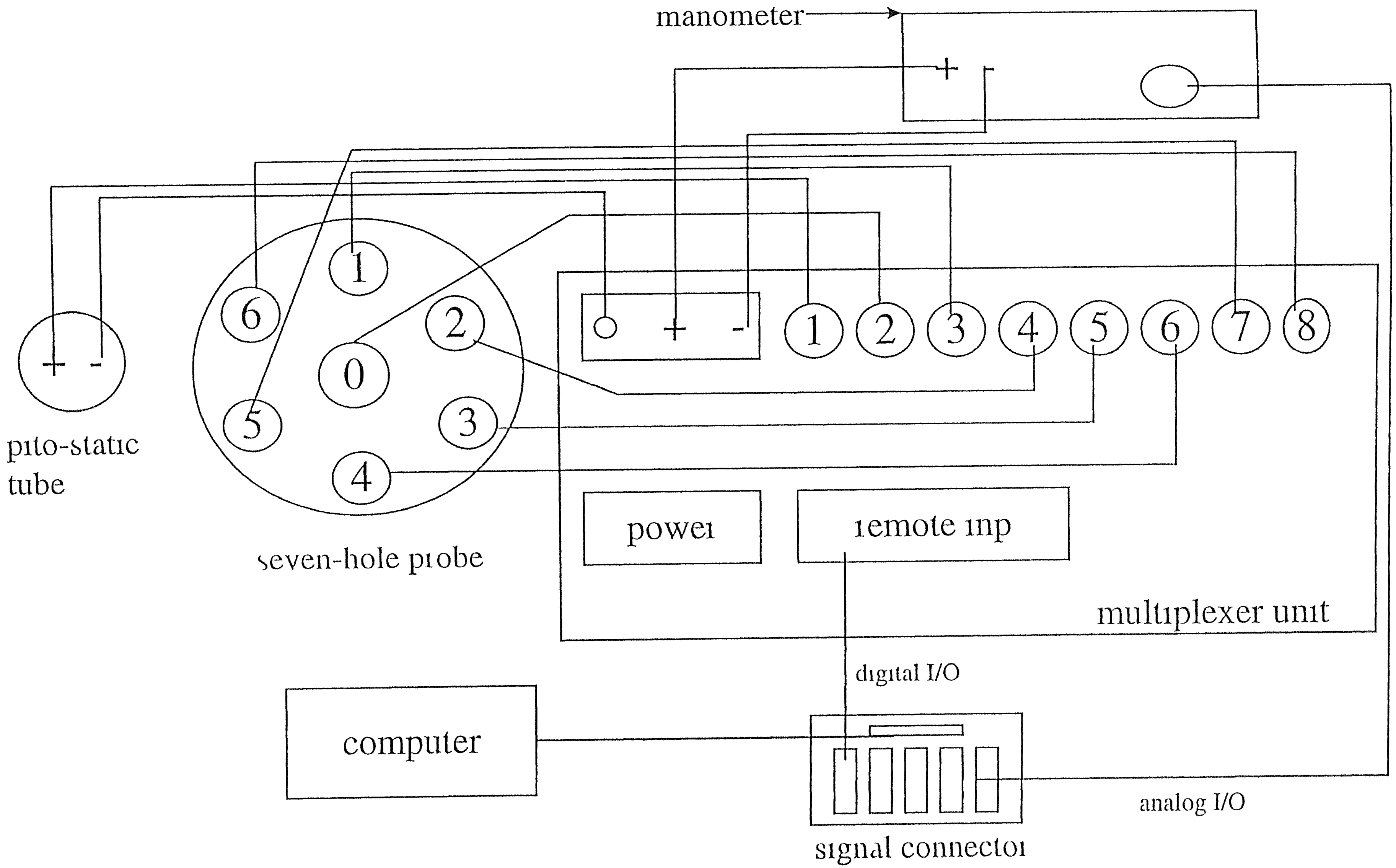


Fig 7 Seven-Hole Probe DAQ Connection

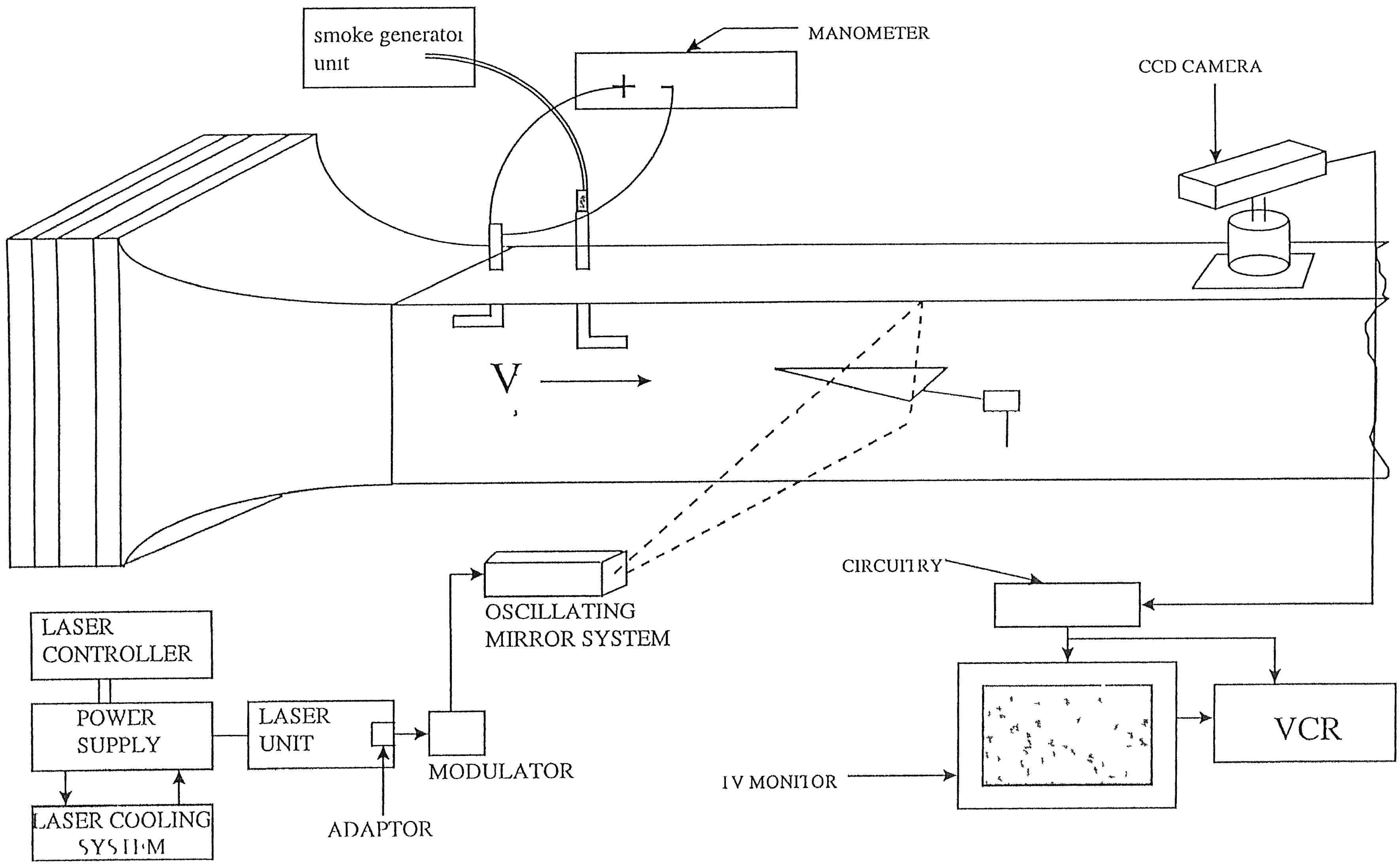
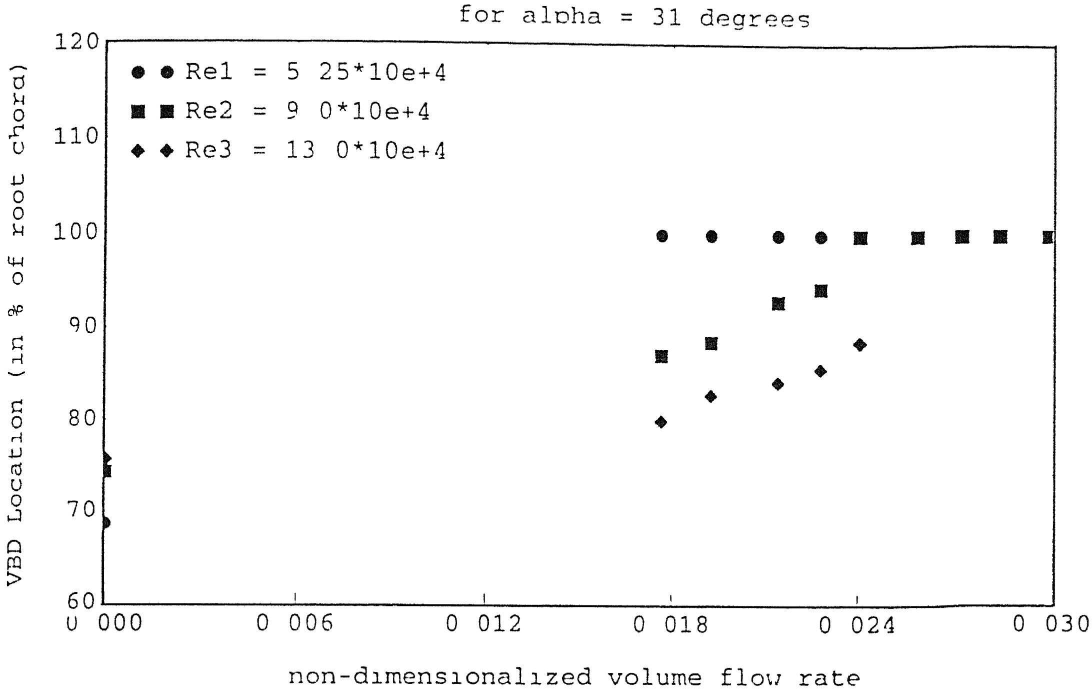


Fig 8 Flow Visualization and Recording Set-up



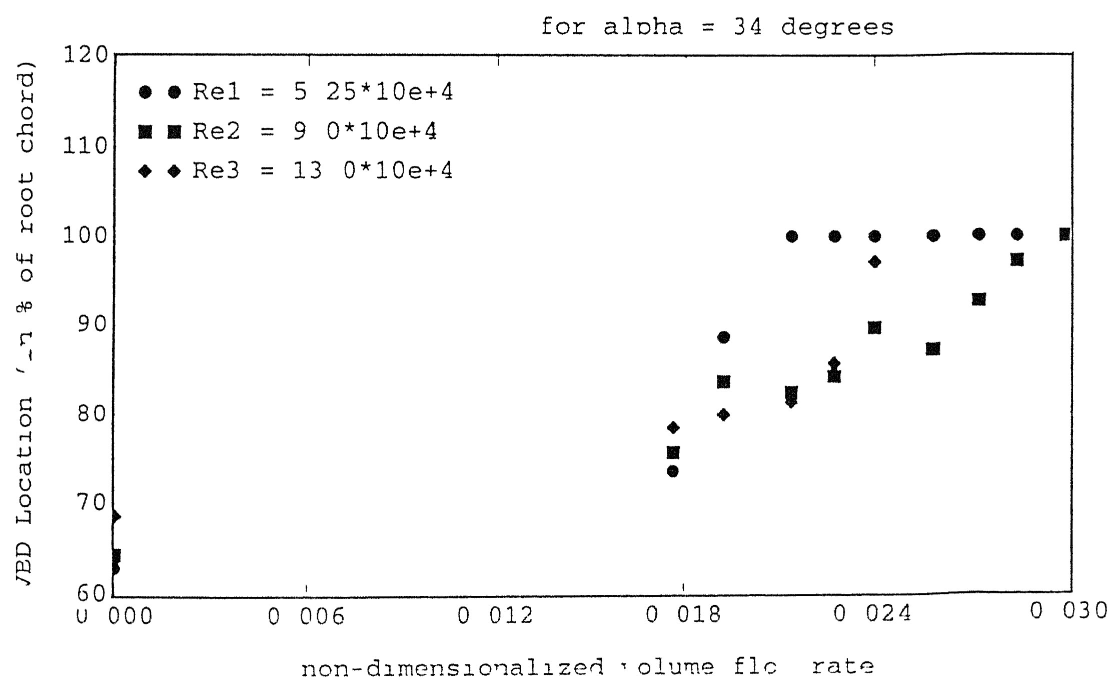
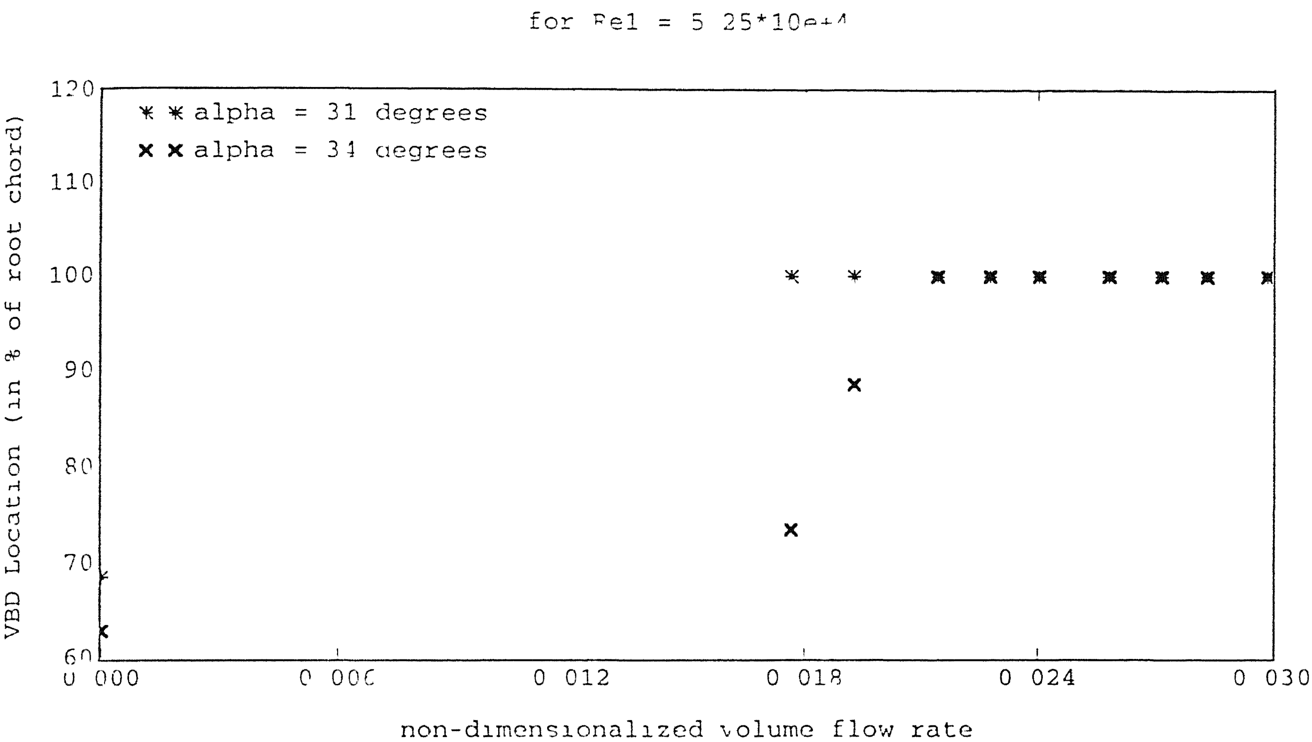


Fig 9 Mass flow rate vs VBD location for different angles of attack



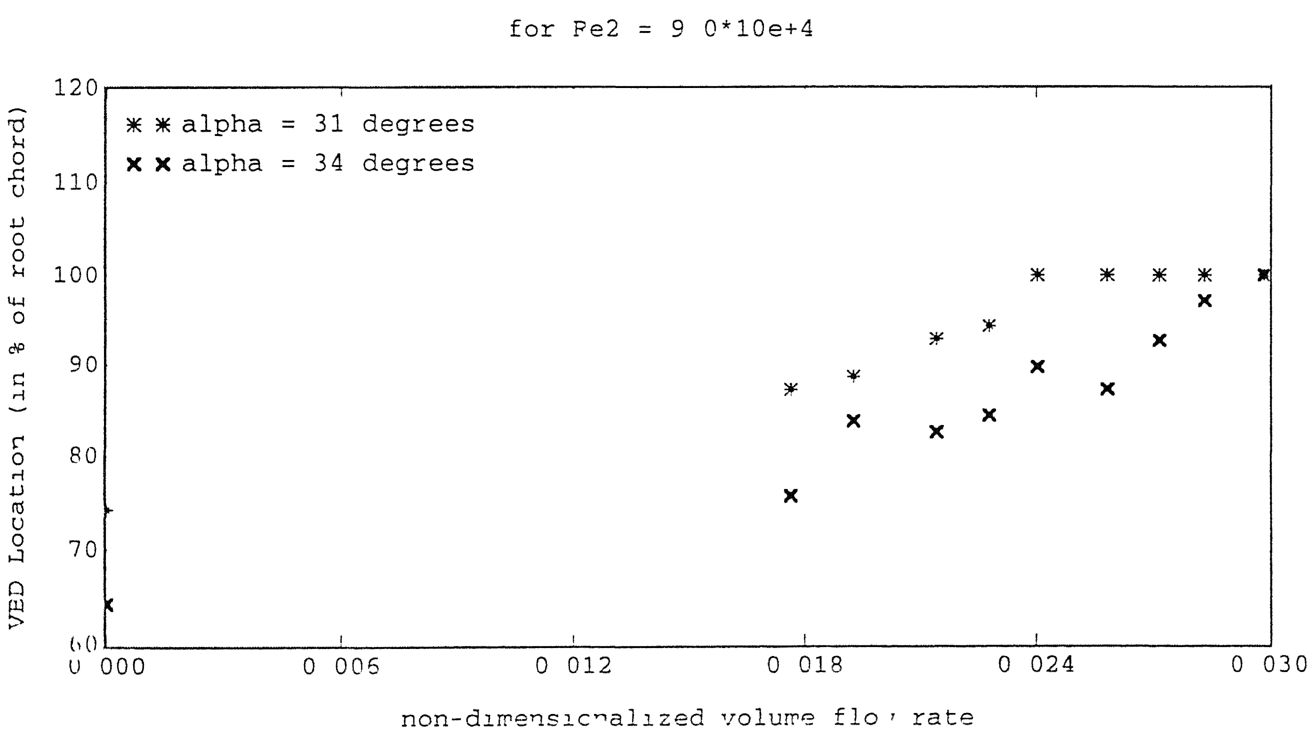


Fig 10 Mass flow rate vs VBD location

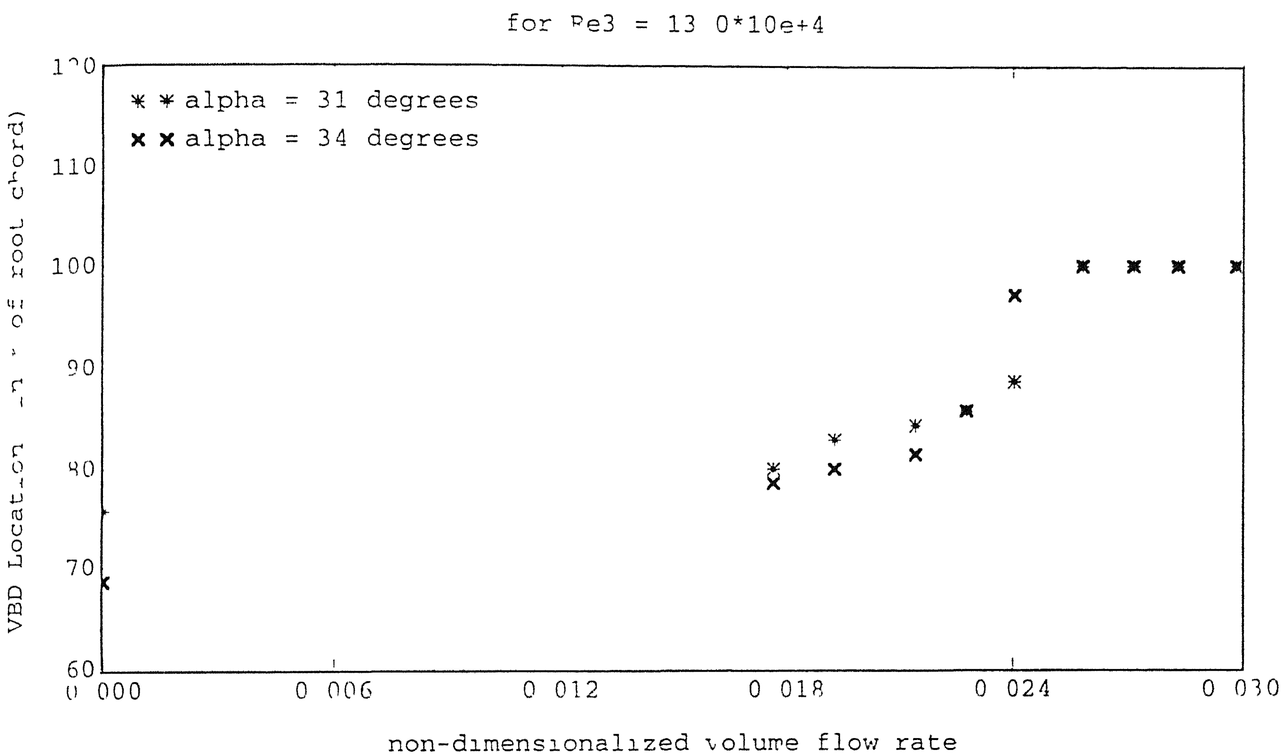


Fig 11 Mass flow rate vs VBD location

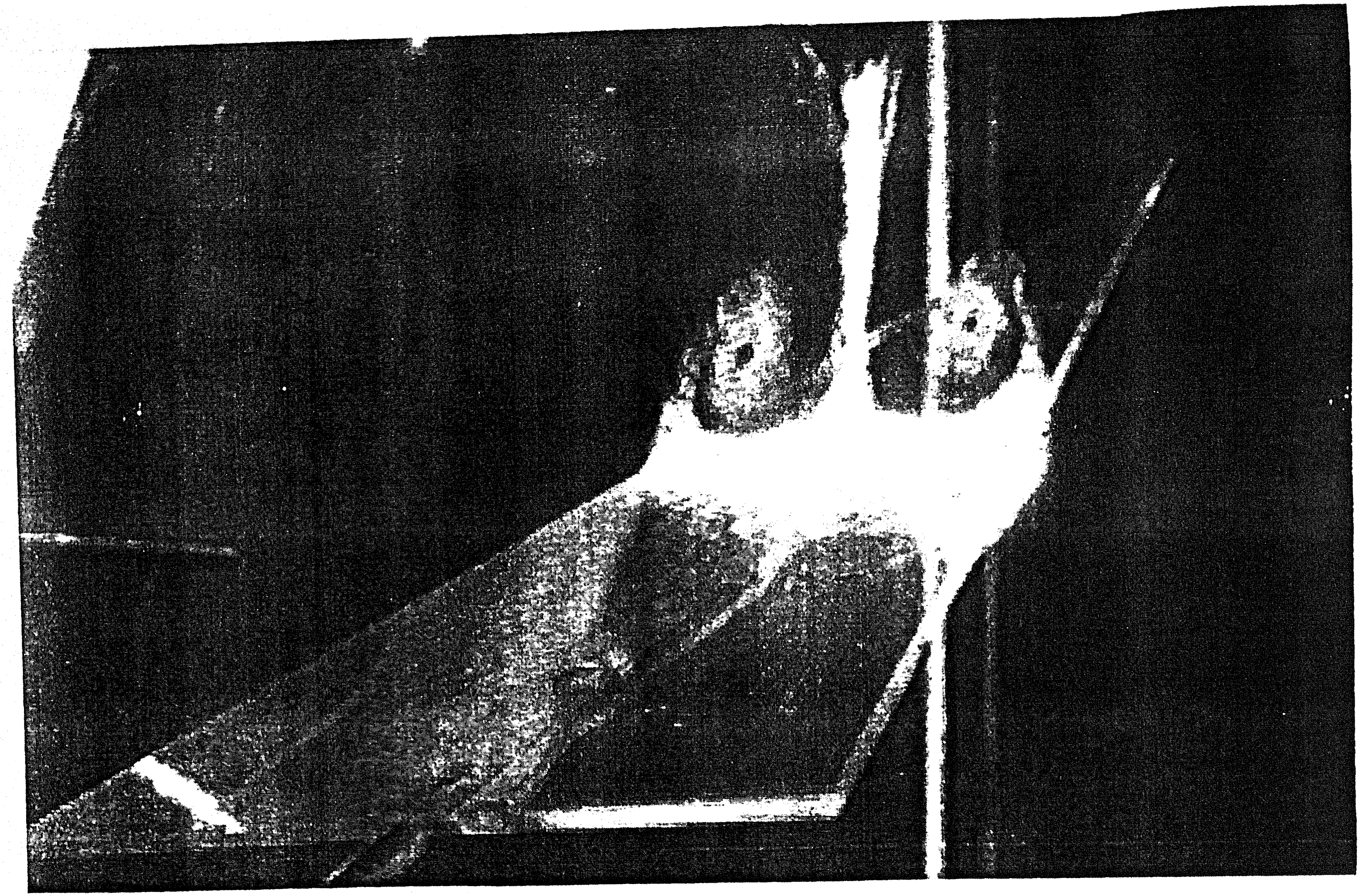


Fig 12. Full Span Vortical Structure

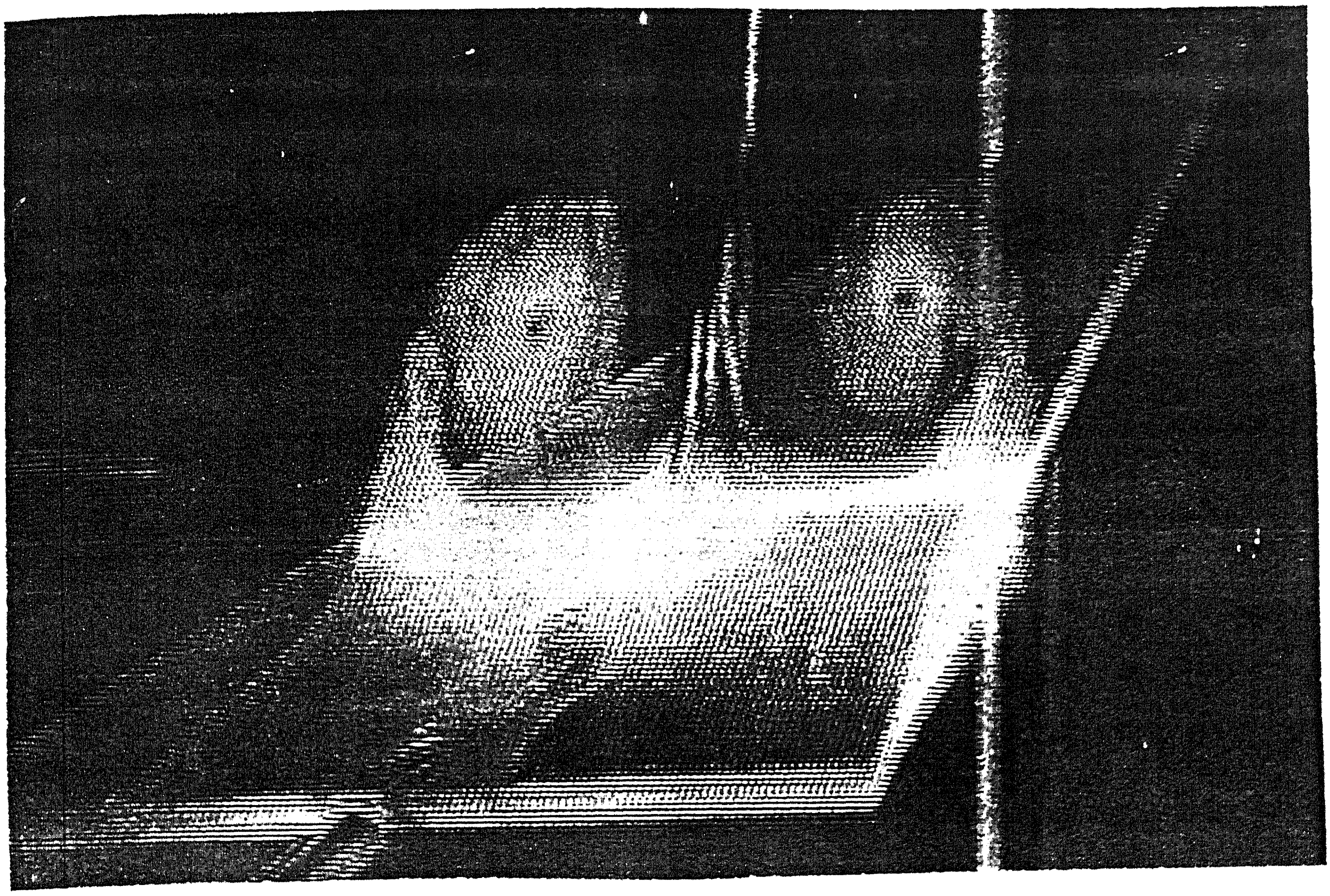


Fig 13a. Beginning of Vortex Breakdown

Fig 13b. Increase in the Vortex Core Diameter

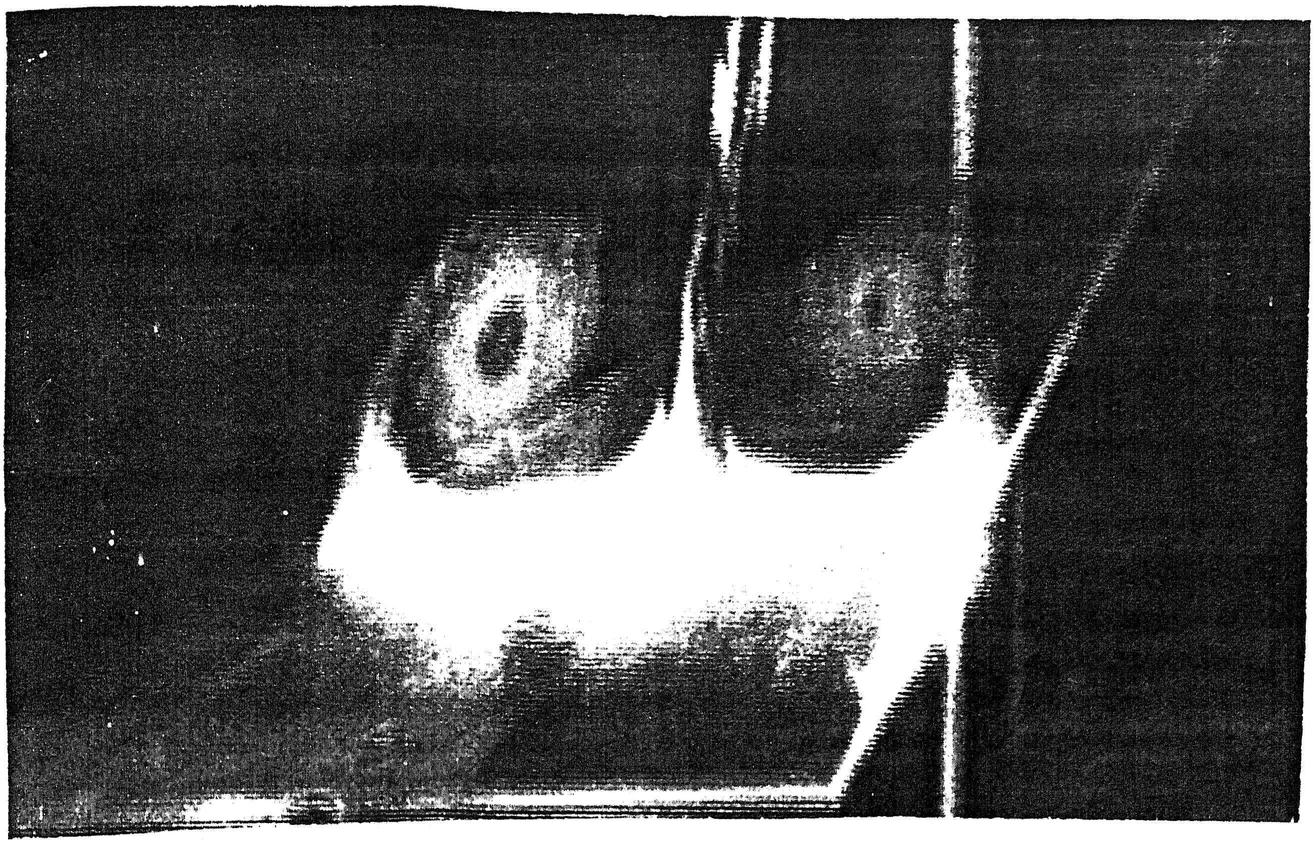


Fig 13c. Vortex Core Diameter Increasing

Fig 13d. Vortex Core Diameter still Increasing

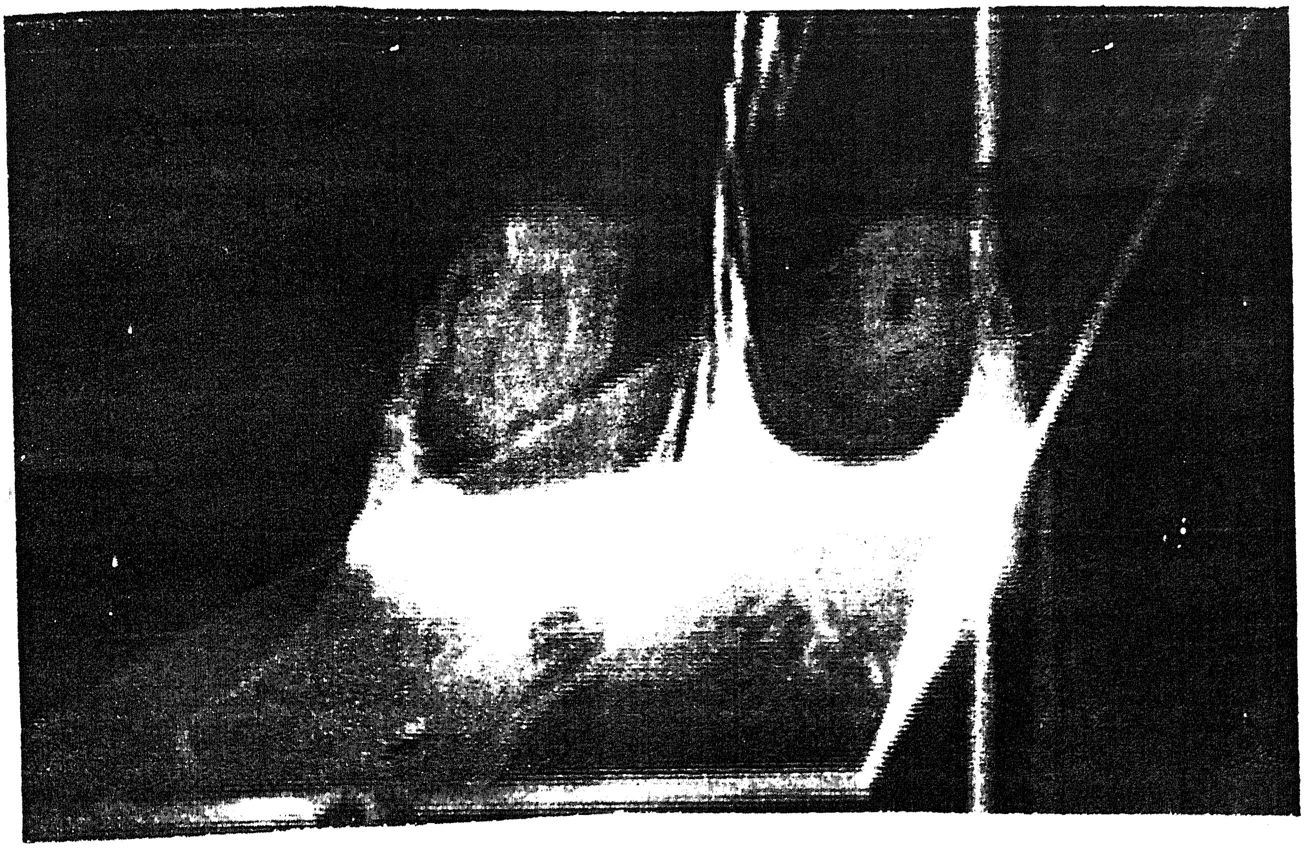


Fig 13e. Vortex Bursting

Fig 13f. Complete Vortex Bursting

Fig 13g. Vortex Core Diameter Reduces

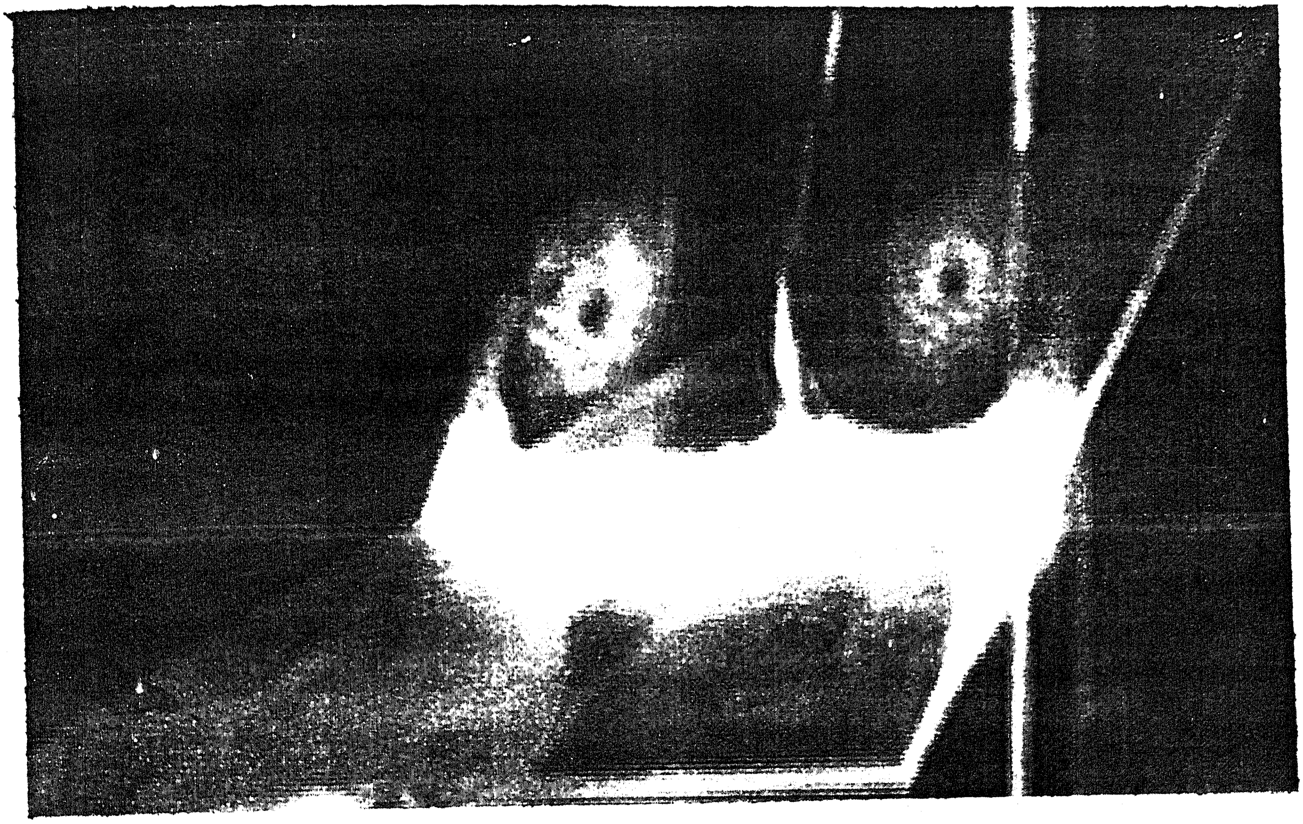


Fig 14a. Vortex Structure with Suction

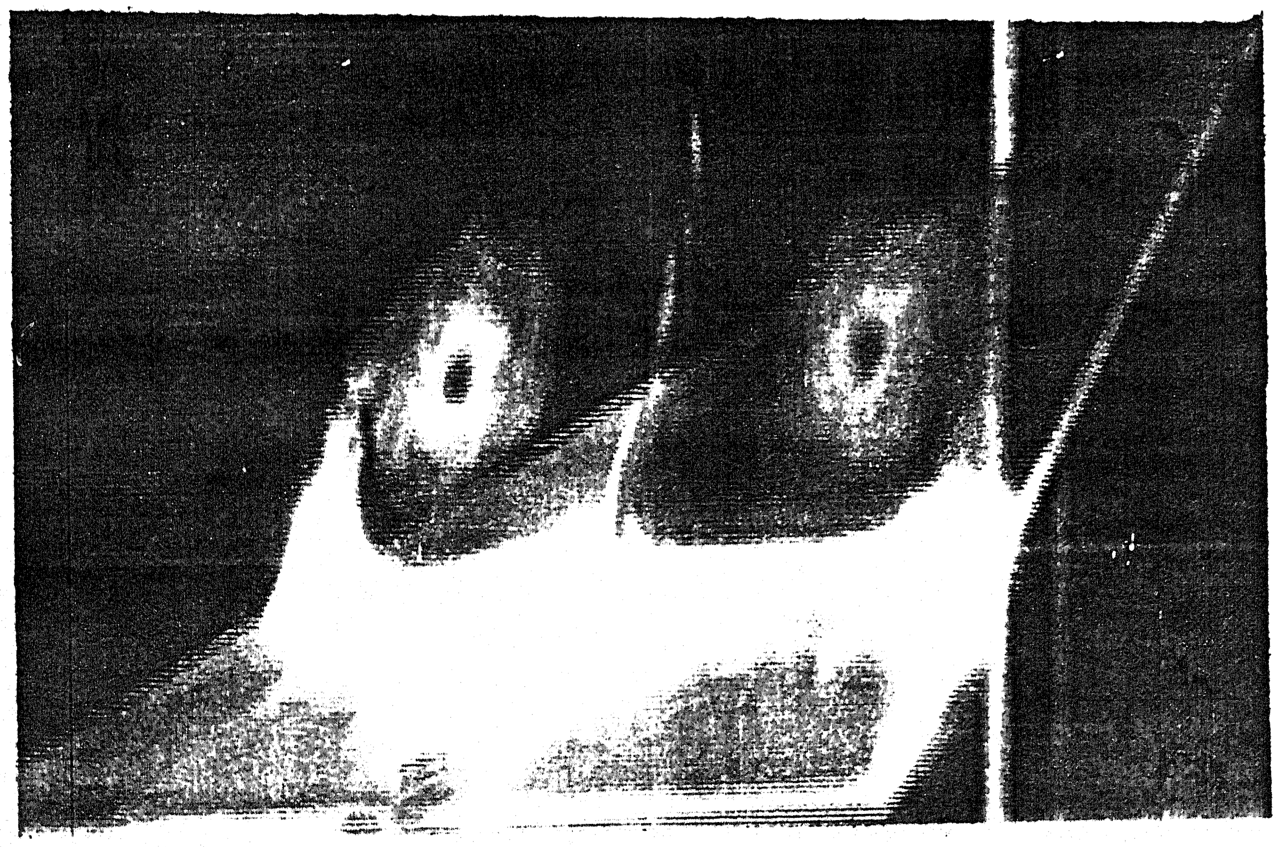


Fig 14b. Vortex Structure with Suction further Downstream

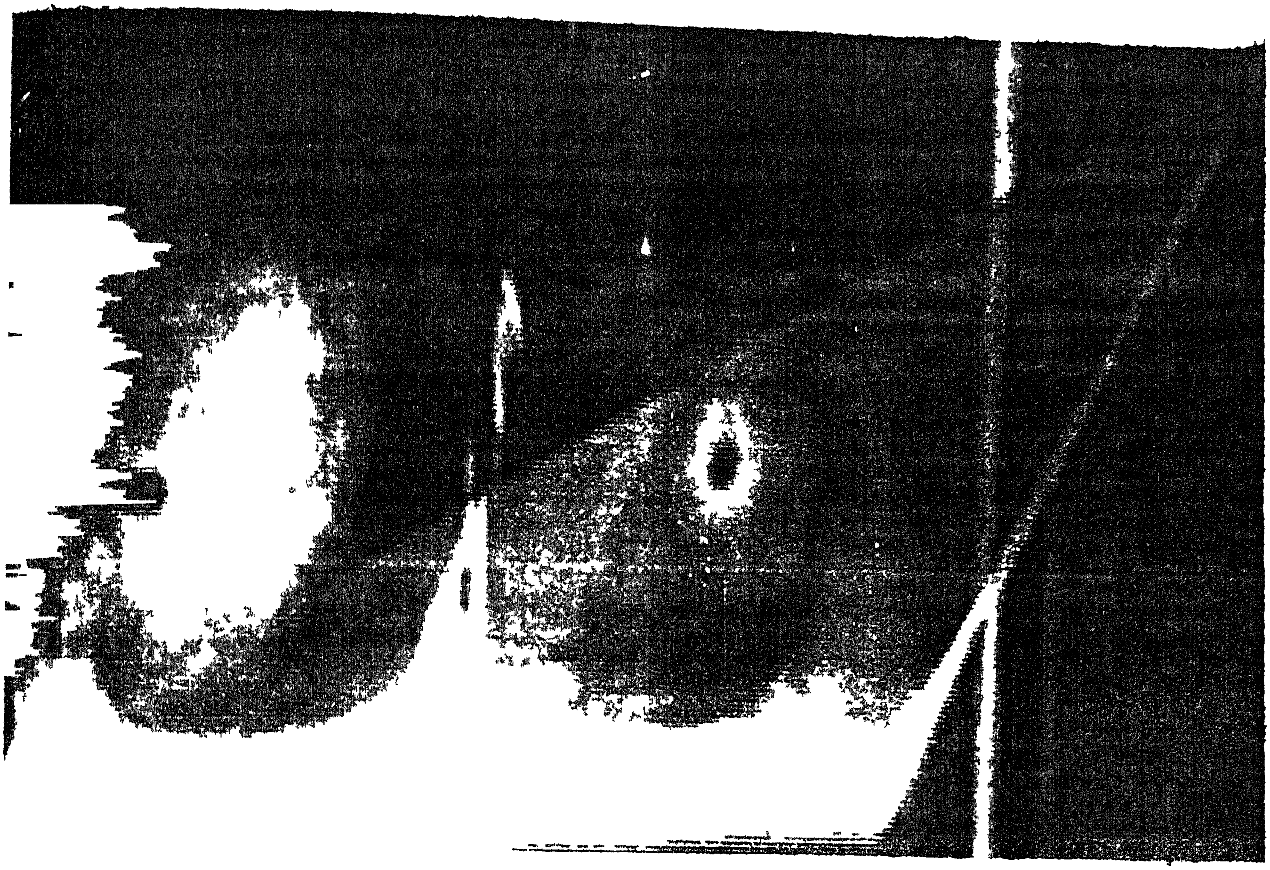


Fig 15a Vortex Bursting at the Probe Tip

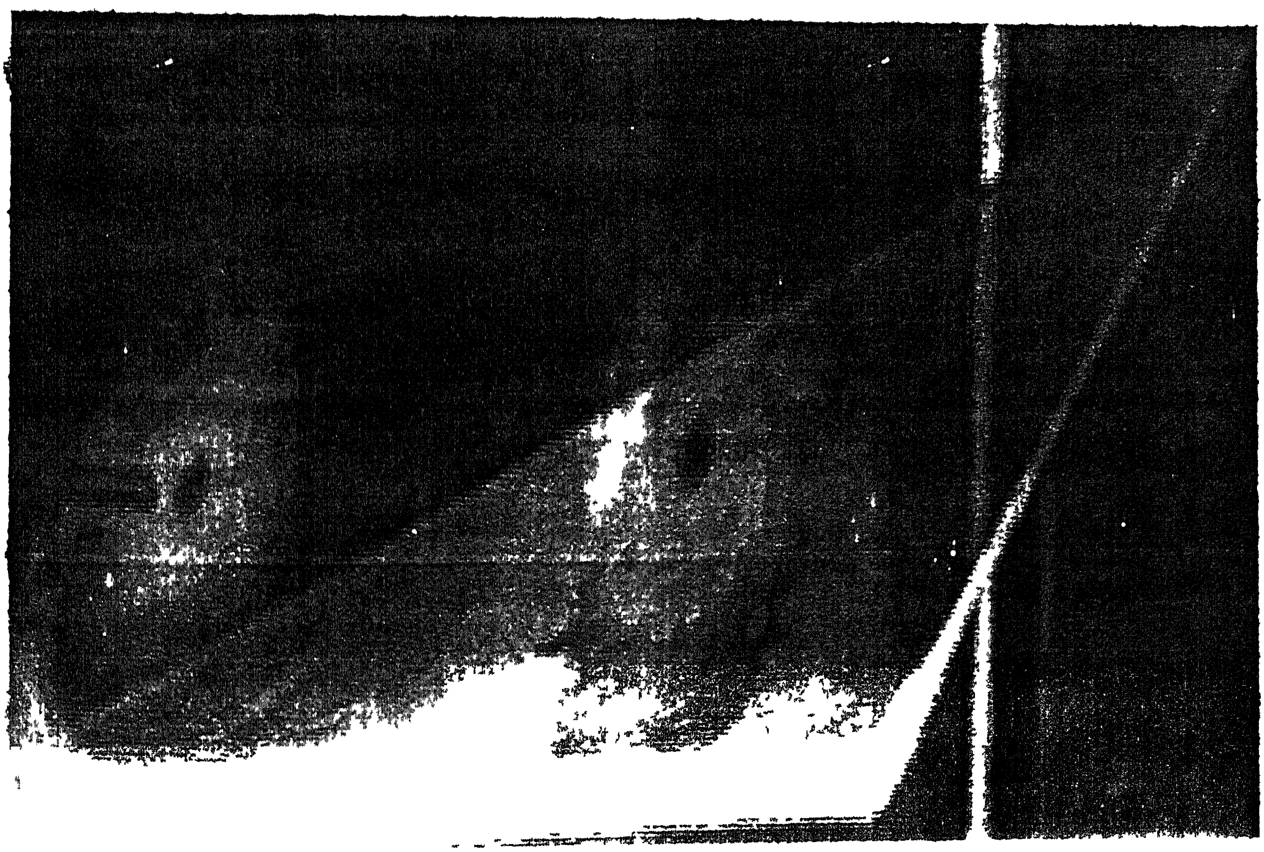
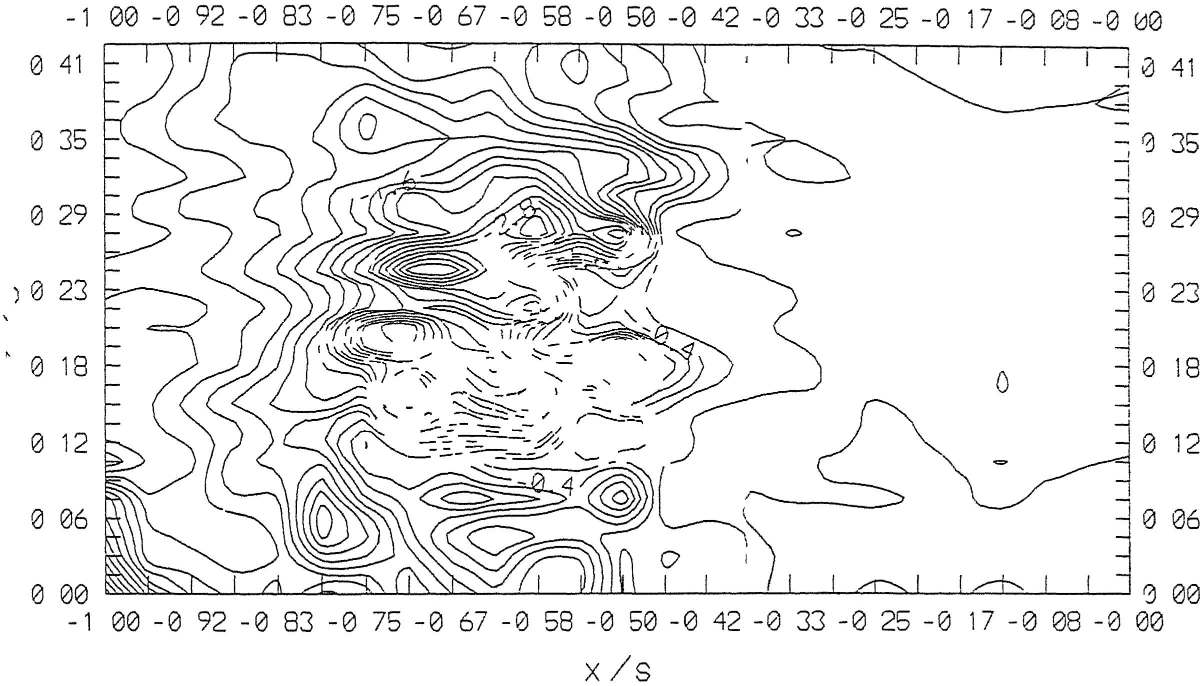


Fig 15b Vortex Bursting at the Probe Tip with Suction

static pressure contour plot



dynamic pressure contour plot

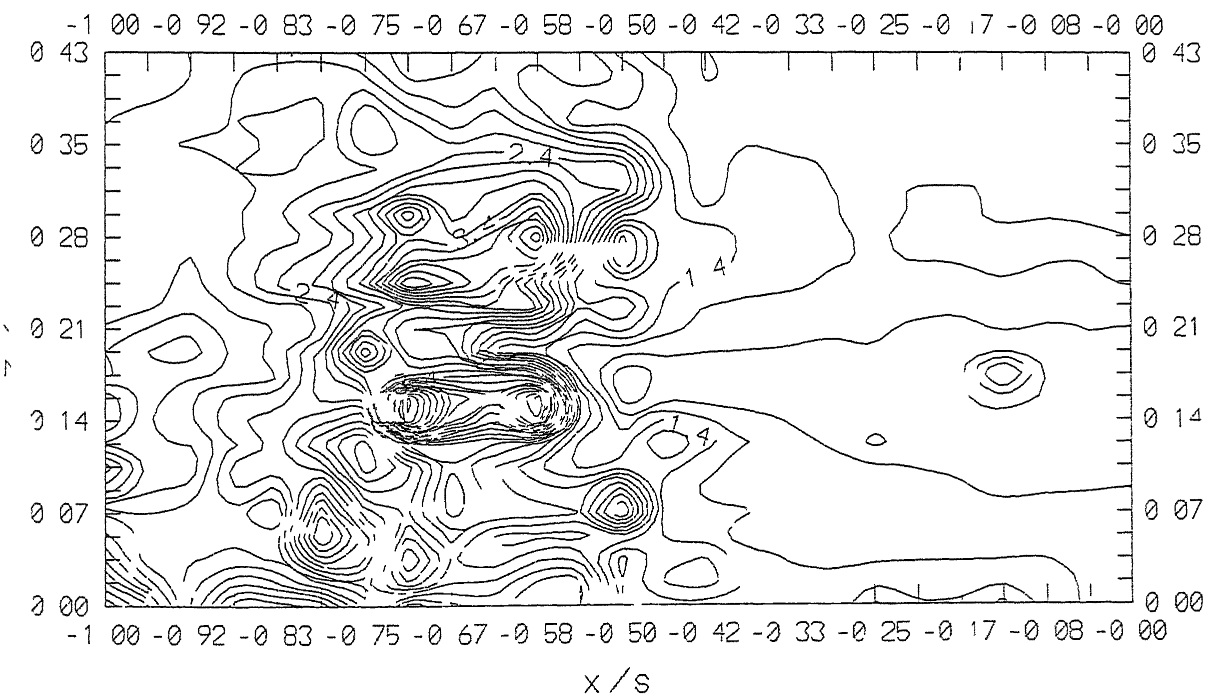


Fig 16 Contour Plots in the Half-plane of Wing

Variac Setting	Δp (in N/m^2)	Friction Factor f	Q (in m^3/min)	V_{av} (in m/s)	$Re_D \times 10^{-4}$
Full Rating	456 68	0 0218	0 458	43 2	4 39
220	256 76	0 0234	0 332	31 31	3 18
210	234 22	0 0237	0 315	29 71	3 02
200	216 58	0 0239	0 302	28 49	2 9
190	197 96	0 0242	0 287	27 07	2 75
180	174 44	0 0246	0 267	25 18	2 56
170	158 76	0 0249	0 253	23 86	2 43
160	143 08	0 0253	0 238	22 45	2 28
150	118 58	0 0259	0 214	20 18	2 05
140	100 94	0 0265	0 196	18 49	1 88

Table[1]

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